**GEOPHYSICAL SURVEY FOR
GROUND WATER EVALUATION
NORTH OF WAIKOLOA VILLAGE
ISLAND OF HAWAII**

DEC. 16, 1991

GEOPHYSICAL SURVEY FOR GROUND WATER EVALUATION NORTH OF WAIKOLOA VILLAGE ISLAND OF HAWAII

Prepared For:

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(BGI Project #91054)

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Table of Contents

1.0 INTRODUCTION

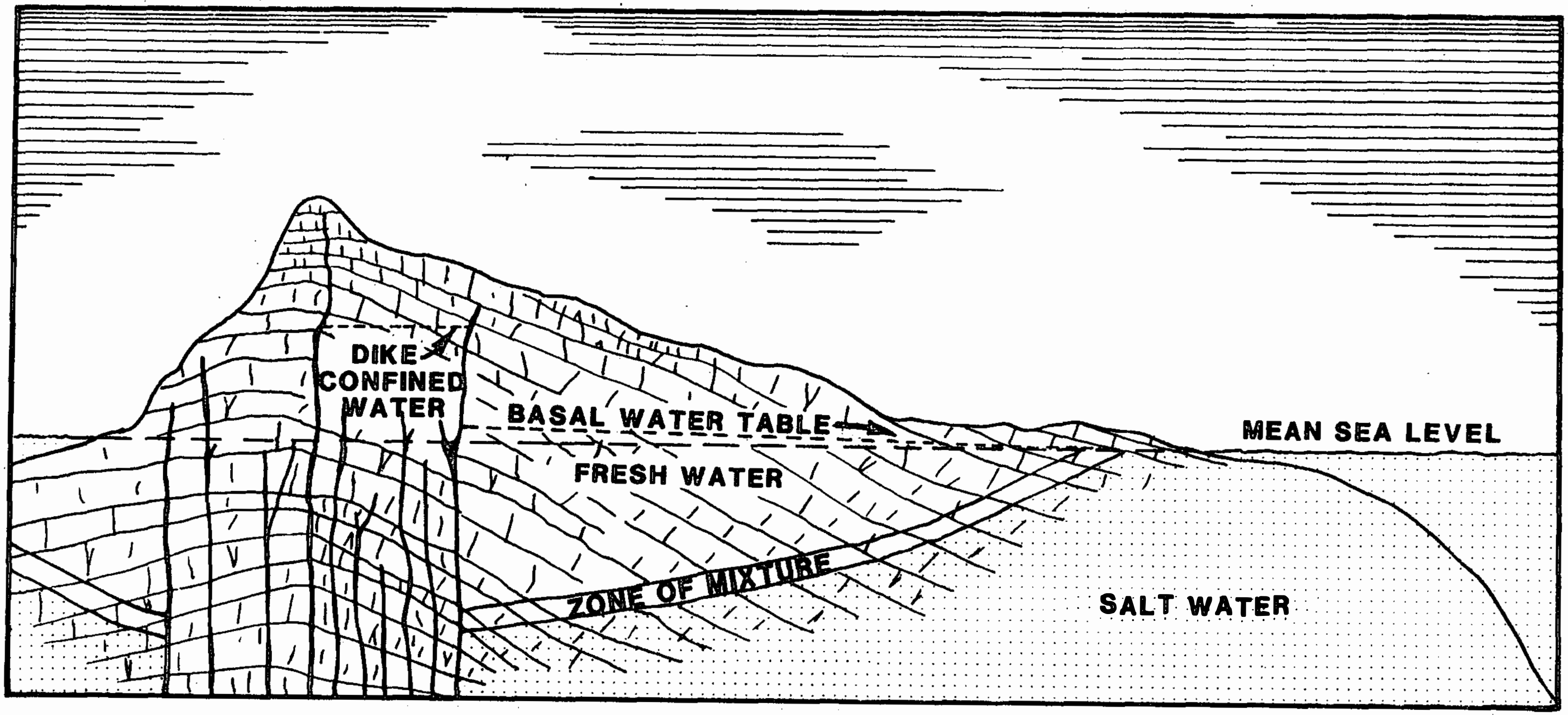
This report contains the results of geophysical time domain electromagnetic (TDEM) surveys performed for ground water resource evaluation north of Waikoloa Village on the Island of Hawaii. The survey was conducted by Blackhawk Geosciences, Inc. (BGI) for Waikoloa Development Company (WDC) during the days of October 28 and November 1, 1991.

The objective of the geophysical survey was to add additional TDEM information to the existing (1988 and 1990) data set along Kamakoa Gulch, North of Waikoloa Village. The concepts for using geophysical surveys for ground water evaluations can be understood using the generalized hydrogeologic cross section shown in Figure 1-1. In the Hawaiian islands, the volcanic rocks are generally highly permeable and rain water rapidly percolates into the ground and migrates downward to the water table. Fresh ground water in island settings is generally found in two environments:

1. <u>Dike-confined waters</u>. Intrusive dikes originating from a magma source below can form ground water dams, and behind these natural dams significant quantities of ground water can be stored.

2. <u>Basal fresh water</u>. The high permeability of the volcanic rocks allows sea water to enter freely under the island, and a delicate balance is reached where a lens of fresh water floats on sea water. In cases where hydrostatic equilibrium exists, the Ghyben-Herzberg relation states that for every foot of fresh water head above sea level there will be 40 ft of fresh water below sea level.

The basal mode water resource was the main focus in the study for WDC. The impetus for using geophysics is that the cost of a geophysical sounding is about one-thousandth the cost of completing a well at elevations above 1,000 ft. Geophysical surveys, combined with other hydrogeologic information, are used to provide optimum locations for well placement and well completion depths.



BLACKHAWK GEOSCIENCES, INC.

SCHEMATIC HYDRO-GEOLOGIC
CROSS SECTION

WAIKOLOA DEVELOPMENT COMPANY
ISLAND OF HAWAII

PROJECT NO: 91054 FIGURE 1-1

2.0 LOGISTICS AND DATA ACQUISITION PROCEDURES

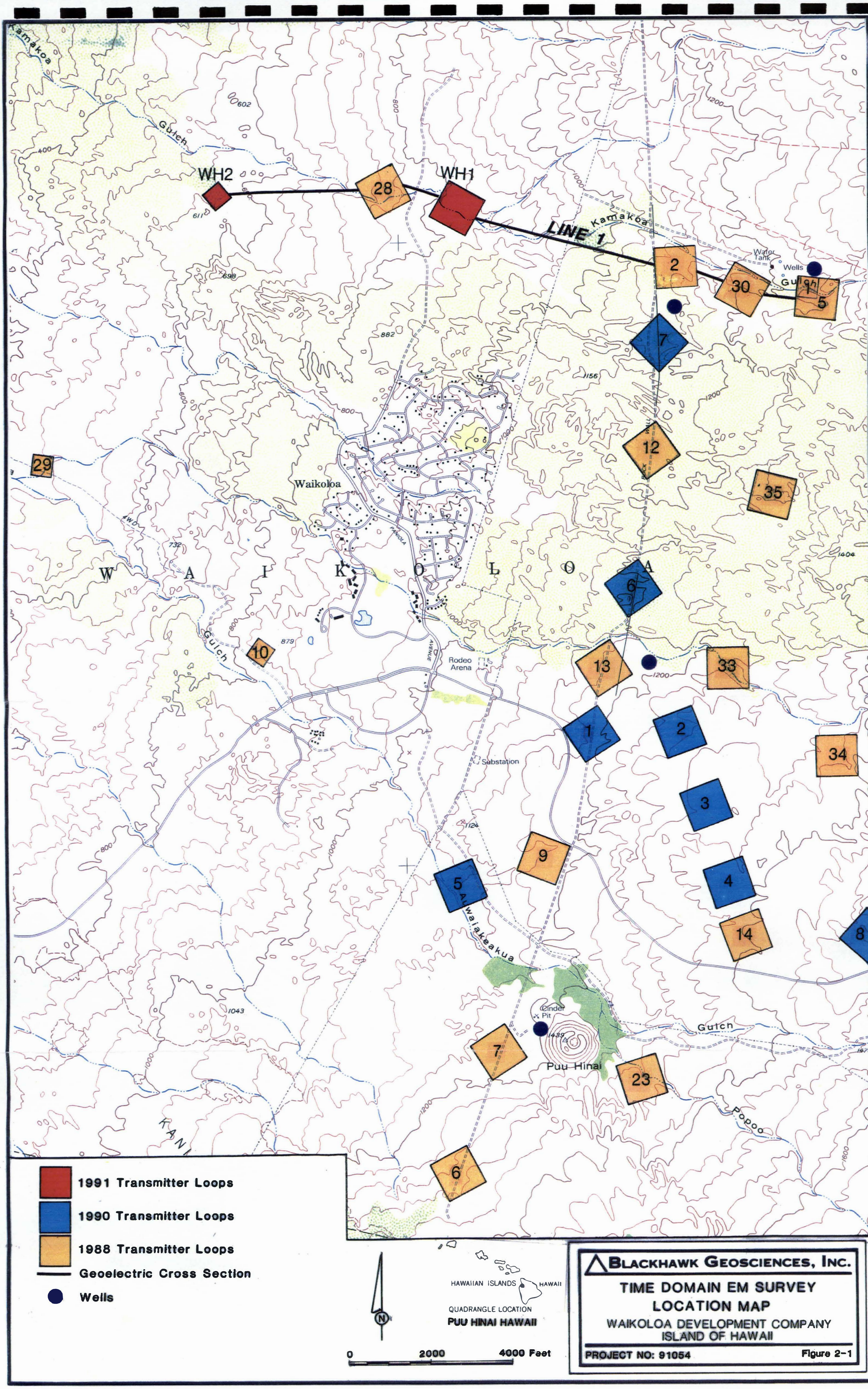
The locations of the transmitter sounding sites were determined in consultation with WDC personnel and their consulting hydrologist. The survey was accomplished by a three man crew with two BGI personnel and one local field helper. During the survey two TDEM soundings were made, one up-hill and another downhill from sounding 28 (1988 data) in Kamakoa Gulch. The sounding locations from the three combined data sets (1988, 1990 and 1991) are shown on Figure 2-1. Transmitter loop sizes varied from 500 ft by 500 ft to 1,000 ft by 1,000 ft in the study area, according to the depth of investigation needed. The elevations of sounding centers were measured with a barometric altimeter to maintain elevation control to within $\pm$ 20 ft. A daily log of field activity is given in Table 2-1.

2.1 PROCEDURES

The Geonics EM-37 TDEM system was utilized on this survey. The system basically consists of a transmitter and a receiver. The transmitter loop is constructed of 10 to 12 gauge insulated copper wire. The wire is laid on the ground surface in a square loop varying in size, depending upon the required depth of investigation (larger loop sizes for deeper measurement). A transmitter and motor generator are connected into the non-grounded loop at one corner. A time-varying current is pulsed through the wire at two different base frequencies. The TDEM receiver measures and records the decay of the vertical magnetic field through a receiver coil placed at the center of the non-grounded transmitter loop. Receiver coils with effective areas of 100 m^2 and 1,000 m^2 were utilized at base frequencies of 3 Hz and 30 Hz. During data acquisition numerous transient decays are collected with the receiver for each sounding. Readings were acquired at several receiver gains with opposite receiver polarities for each sounding location. The readings were stored in a DAS-54 solid state data logger, and were nightly transferred to a personal computer for processing. A technical note is given in Appendix A which describes and illustrates the principles of TDEM.

Table 2-1. Daily log of field activities

Date (1991)	Activity
October 27	Demobilize from other Pacific jobs to Kailua-Kona, HI in conjunction with other surveys.
October 28	Mobilize (one-half day), clear equipment through customs. Meet with Steve Hicks of WDC to discuss survey site locations. Measurement of sounding WH1.
November 1	Measurement of soundings WH2, one-half day field work.
November 4-5	Demobilization of equipment and BGI personnel from Kailua-Kona, HI to Golden, CO.
	(October 29 through 31 and November 2 and 3 were work at other Hawaii locations)



BLACKHAWK GEOSCIENCES, INC.

TIME DOMAIN EM SURVEY
LOCATION MAP

WAIKOLOA DEVELOPMENT COMPANY
ISLAND OF HAWAII

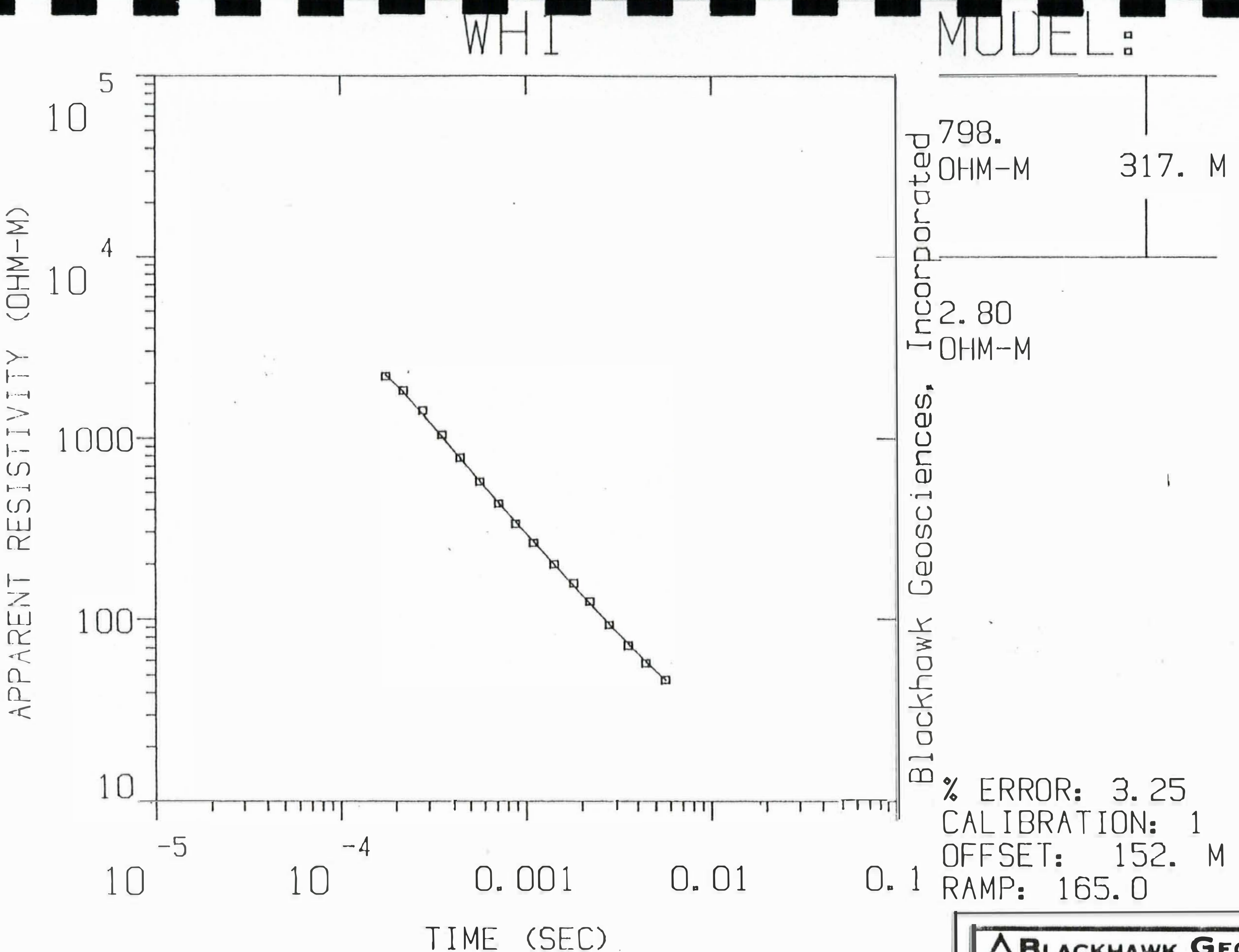
PROJECT NO: 91054

Figure 2-1

3.0 DATA PROCESSING

The following is a brief discussion of the procedures of TDEM data processing. The many data sets for each sounding consisting of measurements at two base frequencies (3 Hz and 30 Hz), different amplifier gain settings and receiver polarities, are combined to produce a transient decay curve over the largest time range possible. The decay curve is transformed into an apparent resistivity curve, which is entered into an automatic ridge regression transient inversion program (ARRTI). From the apparent resistivity curve a one-dimensional model of resistivities and thicknesses is calculated. The inversion program requires an initial model of the geoelectric section, including the number of layers and the resistivities and thicknesses of each of the layers. The program then adjusts these parameters so that the model data converges to best fit the curve formed by the field data set. The inversion program does not change the total number of layers within the model, but allows all other parameters to change freely.

An example data set for sounding WH1 is given in Figures 3-1 and 3-2. Figure 3-1 shows the measured data points (in terms of apparent resistivity) superimposed on the solid line. The solid line represents the computed behavior of the true resistivity layering model shown on the right. For sounding WH1 the geoelectric section is interpreted to consist of two layers, - the first layer has a resistivity of 798 ohm-m with a thickness of 317 m (1,040 ft), and the second layer is fixed at 2.8 ohm-m. Figure 3-2 lists the model and survey parameters with the error between measured and computed data for each time gate in column 4. The apparent resistivity curves and data sheets for both soundings (WH1 and WH2) are contained in Appendix B.



BLACKHAWK GEOSCIENCES, INC.

EXAMPLE DATA SET
SOUNDING WH-1

WAIKOLOA DEVELOPMENT COMPANY
ISLAND OF HAWAII

PROJECT NO: 91054 | Figure 3-1

WH1

MODEL: 2 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		249.9	820.0		
798.18	316.6	-66.6	-218.6	0.4	0.4
2.80					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	1.77E-04	2.18E+03	2.22E+03	-2.103	
2	2.20E-04	1.82E+03	1.80E+03	1.517	
3	2.80E-04	1.41E+03	1.35E+03	4.504	
4	3.55E-04	1.04E+03	1.02E+03	2.420	
5	4.43E-04	7.60E+02	7.61E+02	-0.102	
6	5.64E-04	5.74E+02	5.81E+02	-1.126	
7	7.13E-04	4.33E+02	4.38E+02	-1.105	
8	8.81E-04	3.33E+02	3.41E+02	-2.546	
9	1.10E-03	2.60E+02	2.65E+02	-1.860	
10	1.41E-03	1.98E+02	1.98E+02	0.164	
11	1.80E-03	1.56E+02	1.52E+02	3.098	
12	2.20E-03	1.24E+02	1.21E+02	2.671	
13	2.80E-03	9.25E+01	9.37E+01	-1.255	
14	3.55E-03	7.16E+01	7.34E+01	-2.535	
15	4.43E-03	5.76E+01	5.87E+01	-1.873	
16	5.64E-03	4.67E+01	4.67E+01	0.104	

R: 152. X: 0. Y: 152. DL: 305. REQ: 169. CF: 1.0000
TDHZ ARRAY, 16 DATA POINTS, RAMP: 165.0 MICROSEC, DATA: WH1
2310 0000 0001 Z OPR XTL L 5 10+1000
Ch.21 = 0.165 Ch.22 = 0.89 Ch.23 = 15 Ch.24 = 9
RMS LOG ERROR: 1.39E-02, ANTILOG YIELDS 3.2483 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

P 1	0.91		
F 2	0.00	0.00	
T 1	0.00	0.00	1.00
	P 1	F 2	T 1

BLACKHAWK GEOSCIENCES, INC.

EXAMPLE DATA SET
SOUNDING WH-1
WAIKOLOA DEVELOPMENT COMPANY
ISLAND OF HAWAII

PROJECT NO: 91054

Figure 3-2

4.0 INTERPRETATION RESULTS

4.1 GENERAL

The objective of the geophysical survey for WDC was to infer from the resistivity layering obtained from TDEM soundings, the depth to salt water and the thickness of the basal fresh water lens. The translation of resistivity layering into this hydrogeologic information is generally accomplished by two methods:

1) One method is to use available knowledge about the relation between resistivity values and local hydrogeology. From the TDEM sounding data base (43 soundings) acquired over the Waikoloa area, it has been shown that dry and fresh water saturated volcanic rocks have high resistivities, typically greater than 500 ohm-m. Conversely, volcanic rocks saturated with salt water exhibit resistivities typically less than 5 ohm-m. Using this knowledge, the characteristic ranges of resistivities expected for local geohydrologic units in the Waikoloa survey area are shown in Figure 4-1.

2) Another method is to calibrate the geophysical interpretation at a well. In this case several wells were made available for comparison in the 1988 and 1990 Waikoloa surveys. The most recent comparison is a well drilled in 1988 between soundings 13 and 33 (Fig. 2-1). In this well fresh water was reported at about 8 ft above sea level, which is in good agreement with the 1988 and 1990 TDEM survey results. From these survey results a 2.8 ohm-m value was interpreted to represent the resistivity of the basal salt water. The resistivity of the basal salt water was fixed at this value for all interpretations.

Therefore, where a conductive layer (less than 5 ohm-m) is detected below sea level, this layer is expected to represent salt water saturated volcanics. From the interpreted depth to the salt water layer the thickness of the fresh/brackish water lens and static water level (head) can subsequently be calculated using the Ghyben-Herzberg principle. This principle states that for every foot of fresh water above sea level there will be about 40 feet of fresh water below sea level. An illustration of the Ghyben-Herzberg principle is given in Figure 4-2.

4.2 GEOELECTRIC CROSS SECTION

The results of the two TDEM soundings (WH1 and WH2) are combined with four previously acquired soundings (1988 data) to produce a geoelectric cross section along Kamakoa Gulch, which is shown in Figure 4-3. Layers with similar resistivity values have been linked together in the cross section.

Line 1

The geoelectric cross section for the six soundings along the Kamakoa Gulch are shown as a west to east line in Figure 4-3. The upper layer in the cross section is shown to have high resistivities ranging from 439 ohm-m at sounding 28 to greater than 3500 ohm-m at sounding 5. This high resistivity layer is interpreted to represent dry unweathered volcanics above sea level, and below sea level volcanic rocks saturated with fresh/brackish water. The lower layer in the section is interpreted to represent salt water saturated volcanics and the resistivity of this layer has been fixed at 2.8 ohm-m. The thickness of the fresh/brackish water lens for the geoelectric cross section was found to vary from approximately 136 ft at sounding WH2 to 740 ft beneath sounding 30.

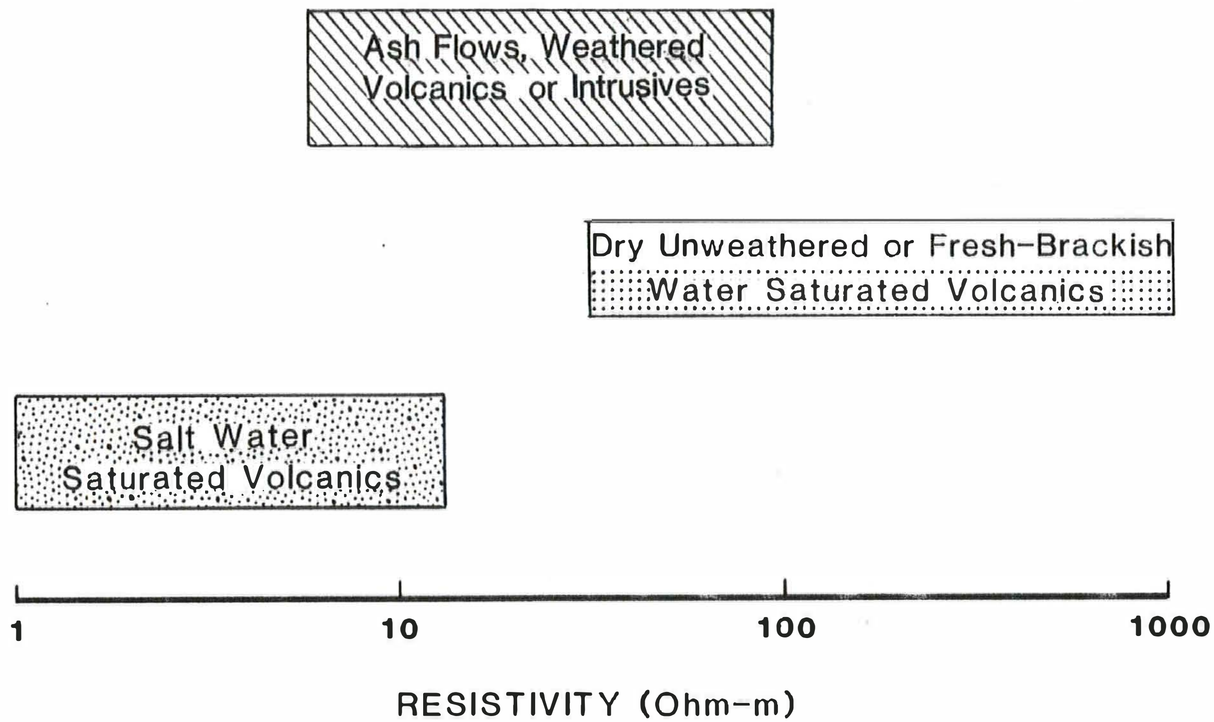
4.3 HYDROGEOLOGIC INTERPRETATIONS

Table 4-1 lists the approximate thicknesses of the fresh/brackish water lens calculated from the elevation of the salt water interface interpreted from the TDEM soundings. The table includes the 1991 soundings as well as the 1988 soundings that are incorporated into the geoelectric cross section of Figure 4-3, and the value of static water level (head) calculated by using the Ghyben-Herzberg principle.

Table 4-1. Hydrogeologic information derived from TDEM soundings (values in feet)

Sounding # (Year)	Surface Elevation	Elevation of Conductive Layer	Calculated Static Water Level (head)	Approximate Thickness of Fresh/ Brackish Water Lens
WH2 (1991)	550	-136	3.4	139
28 (1988)	740	-177	4.4	181
WH1 (1991)	820	-219	5.5	225
2 (1988)	1110	-630	15.8	645
30 (1988)	1220	-740	18.5	758
5 (1988)	1245	-696	17.4	713

The additional soundings acquired on this survey were included into the data base for the Waikoloa survey area to produce a revised contour map of the depth to the salt water interface. Figure 4-4 displays the contour map. The additional data confirms the location of the -200 ft contour across Kamakoa Gulch, and helps to delineate the approximate location of the -150 ft contour which occurs at about the 600 ft elevation level through the gulch. The -150 ft contour has been extrapolated over a large distance and is dashed where data density is limited. The additional data causes the contours to shift to the west and be separated by greater distances between soundings WH1 and 2. This decreases the gradient in depth of salt water (and head) when compared to the 1990 contour map.

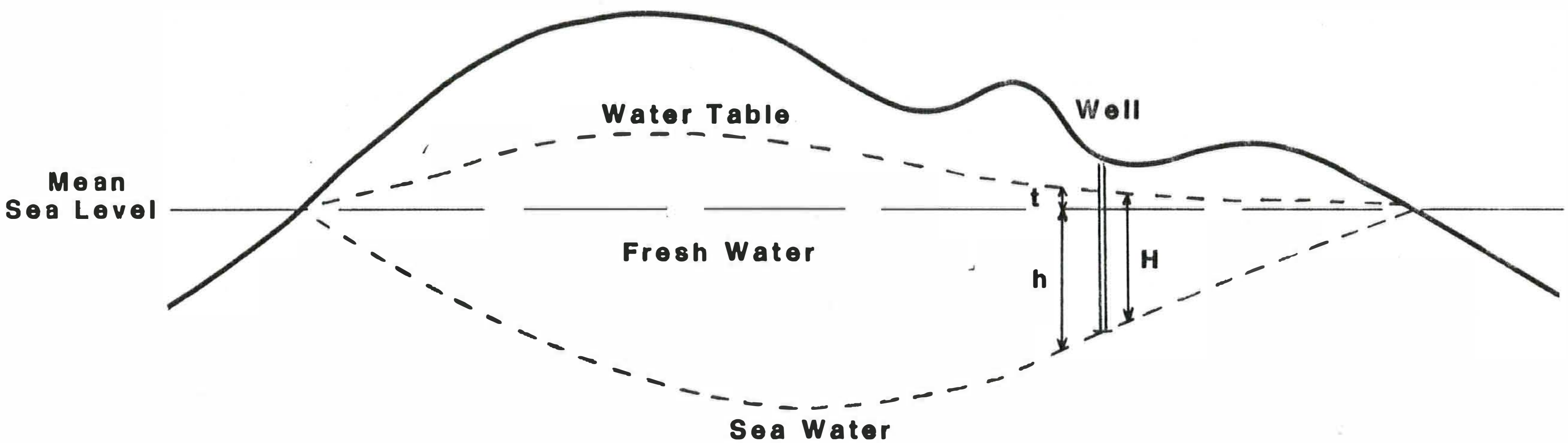


BLACKHAWK GEOSCIENCES, INC.

CHARACTERISTIC RESISTIVITY RANGES
WAIKOLOA DEVELOPMENT COMPANY
ISLAND OF HAWAII

PROJECT NO: 91054

Figure 4-1



$t = 1/40\ (h)$

FROM: HERZBERG

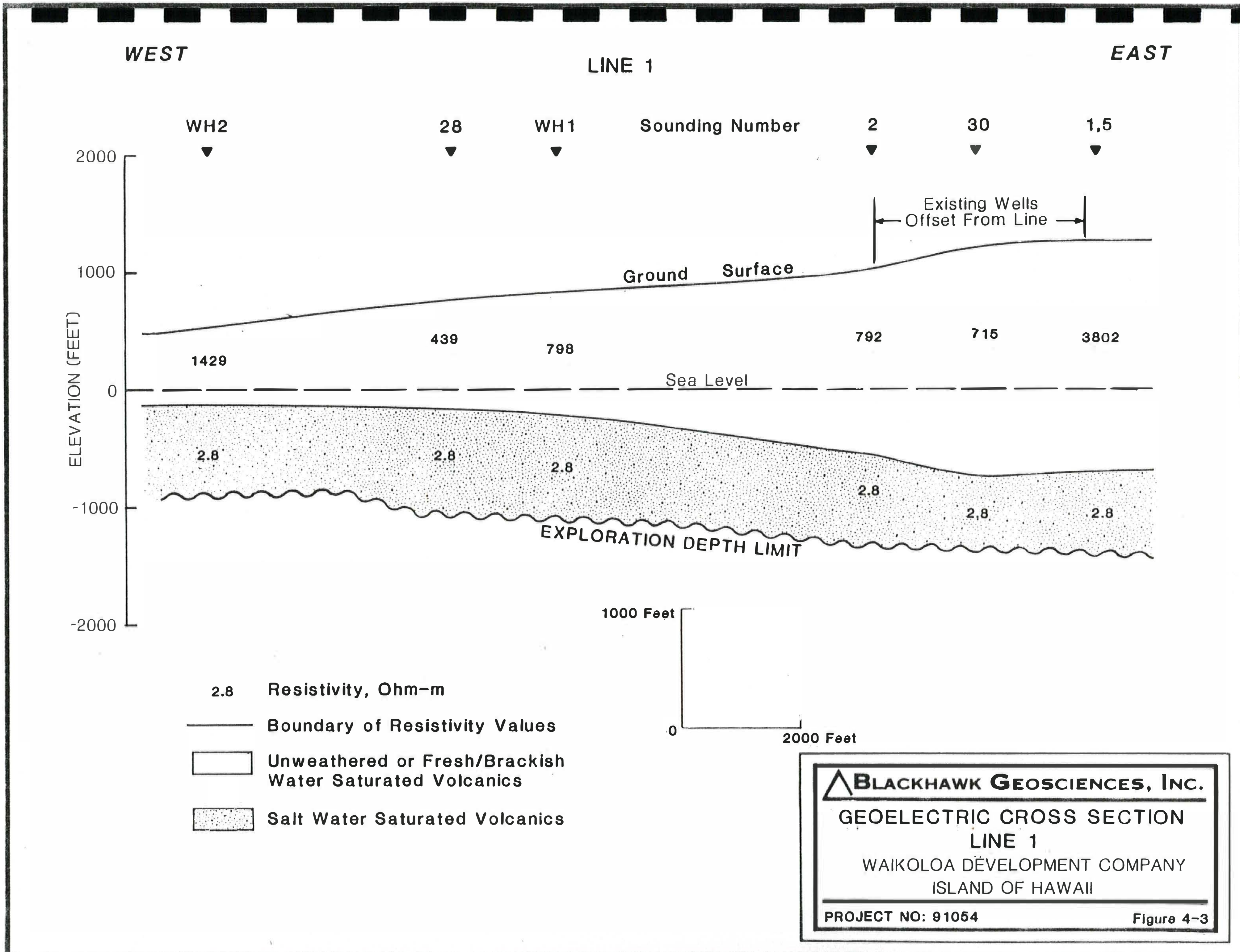
BLACKHAWK GEOSCIENCES, INC.

Illustration of the
Ghyben-Herzberg Principle

WAIKOLOA DEVELOPMENT COMPANY
ISLAND OF HAWAII

PROJECT NO: 91054

Figure 4-2



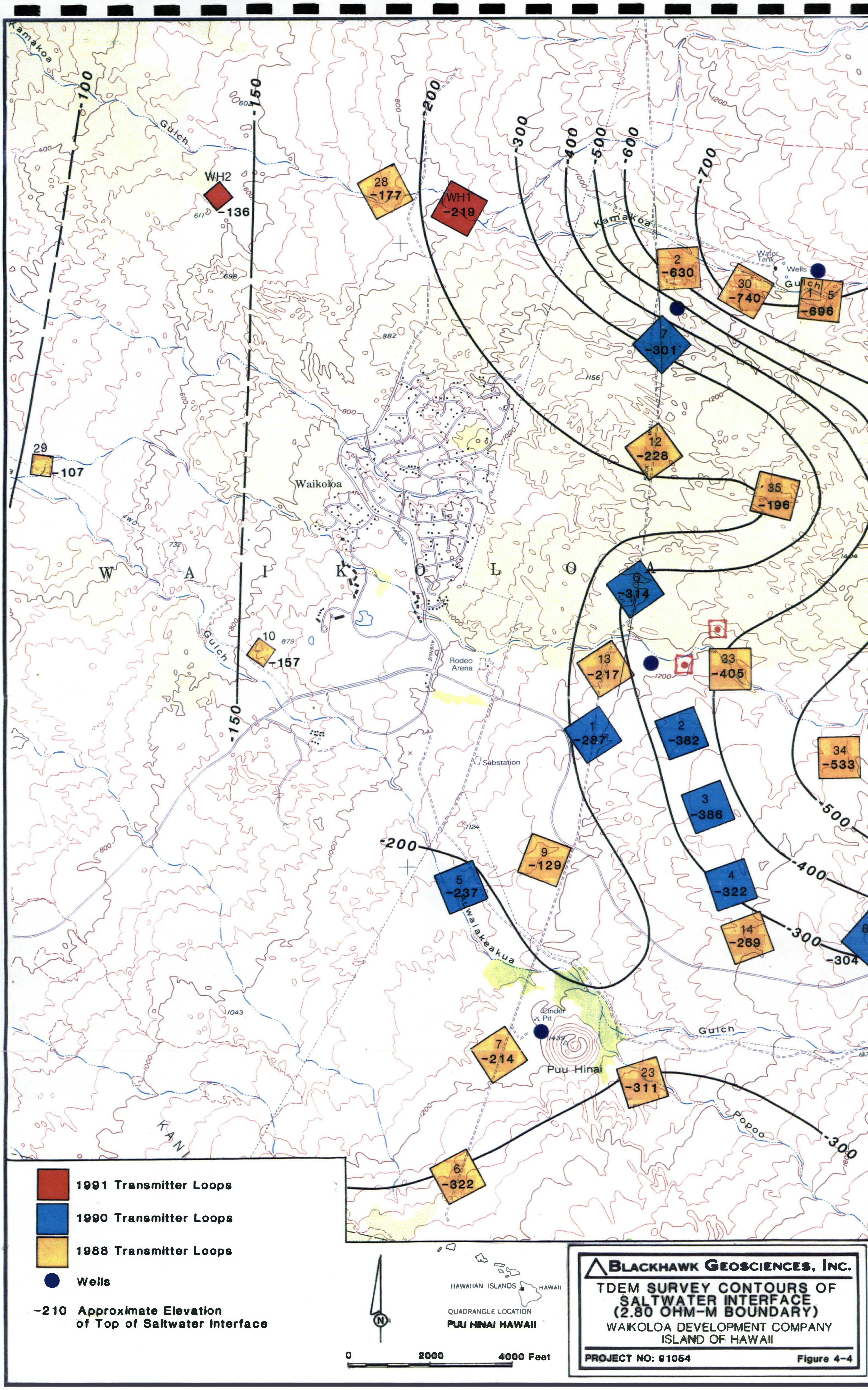
BLACKHAWK GEOSCIENCES, INC.

GEOELECTRIC CROSS SECTION
LINE 1

WAIKOLOA DEVELOPMENT COMPANY
ISLAND OF HAWAII

PROJECT NO: 91054

Figure 4-3

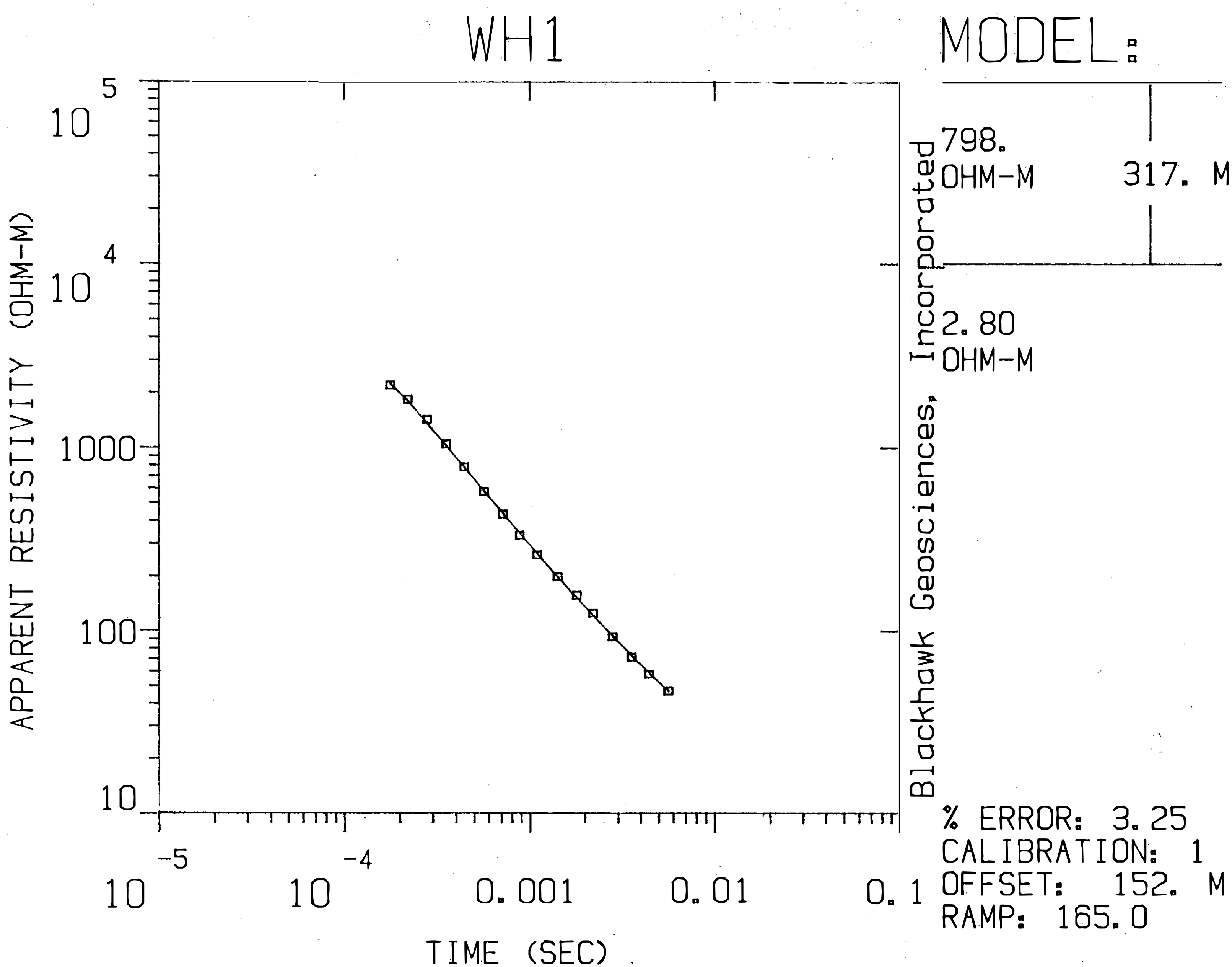


1991 Transmitter Loops
1990 Transmitter Loops
1988 Transmitter Loops
Wells
-210 Approximate Elevation of Top of Saltwater Interface
HAWAIIAN ISLANDS
HAWAII
QUADRANGLE LOCATION
PUU HINAI HAWAII
0 2000 4000 Feet
BLACKHAWK GEOSCIENCES, INC.
TDEM SURVEY CONTOURS OF SALTWATER INTERFACE (2.80 OHM-M BOUNDARY)
WAIKOLOA DEVELOPMENT COMPANY
ISLAND OF HAWAII
PROJECT NO: 91054
Figure 4-4
W A I K O L O A
Waikoloa
Kamakoa Gulch
Rodeo Arena
Substation
Cinder Pit
Puu Hinai
Water Tank
Wells
WH2 -136
28 -177
WH1 -219
2 -630
30 -740
1 5 -696
7 -301
12 -228
35 -196
29 -107
10 -157
6 -314
13 -217
33 -405
1 -287
2 -382
34 -533
3 -386
9 -129
5 -237
4 -322
14 -269
8 -304
7 -214
23 -311
6 -322

5.0 CONCLUSIONS

The main objective of the TDEM surveys is to assist in ground water resource evaluation. Two TDEM soundings were taken during this survey to add to the existing data base (43 soundings) acquired during 1988 and 1990, so that particularly along the Kamakoa Gulch north of Waikoloa Village the existing information could be refined. The additional data was used to revise the contour map of the elevation of salt water in this area.

The interpretation of the data collected in this 1991 survey shows good agreement with interpretations from data taken along Kamakoa Gulch in 1988. The revised contour map confirms the location of the -200 ft contour and shows a slight shift of the contours to the west of the Waikoloa well field (between soundings WH1 and 2). This causes a slight decrease in the steep gradient in depth to salt water interface compared to the 1990 contour map. Sounding WH2 near the proposed water treatment plant shows an approximate thickness of the fresh/brackish water lens of 136 ft, or an estimated head of 3.4 ft, computed by the Ghyben-Herzberg relation. This relatively thin basal mode water lens would most likely be brackish water in the area of sounding WH2.



WH1
MODEL:
798.
OHM-M
317. M
2.80
OHM-M
APPARENT RESISTIVITY (OHM-M)
10^5
10^4
1000
100
10
10^{-5}
10^{-4}
0.001
0.01
0.1
TIME (SEC)
Blackhawk Geosciences, Incorporated
% ERROR: 3.25
CALIBRATION: 1
OFFSET: 152. M
RAMP: 165.0

MODEL: 2 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		249.9	820.0		
798.18	316.6	-66.6	-218.6	0.4	0.4
2.80					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	1.77E-04	2.18E+03	2.22E+03	-2.103	
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5	4.43E-04	7.80E+02	7.81E+02	-0.102	
6	5.64E-04	5.74E+02	5.81E+02	-1.126	
7	7.13E-04	4.33E+02	4.38E+02	-1.105	
8	8.81E-04	3.33E+02	3.41E+02	-2.546	
9	1.10E-03	2.60E+02	2.65E+02	-1.860	
10	1.41E-03	1.98E+02	1.98E+02	0.164	
11	1.80E-03	1.56E+02	1.52E+02	3.098	
12	2.20E-03	1.24E+02	1.21E+02	2.671	
13	2.80E-03	9.25E+01	9.37E+01	-1.255	
14	3.55E-03	7.16E+01	7.34E+01	-2.535	
15	4.43E-03	5.76E+01	5.87E+01	-1.873	
16	5.64E-03	4.67E+01	4.67E+01	0.104	

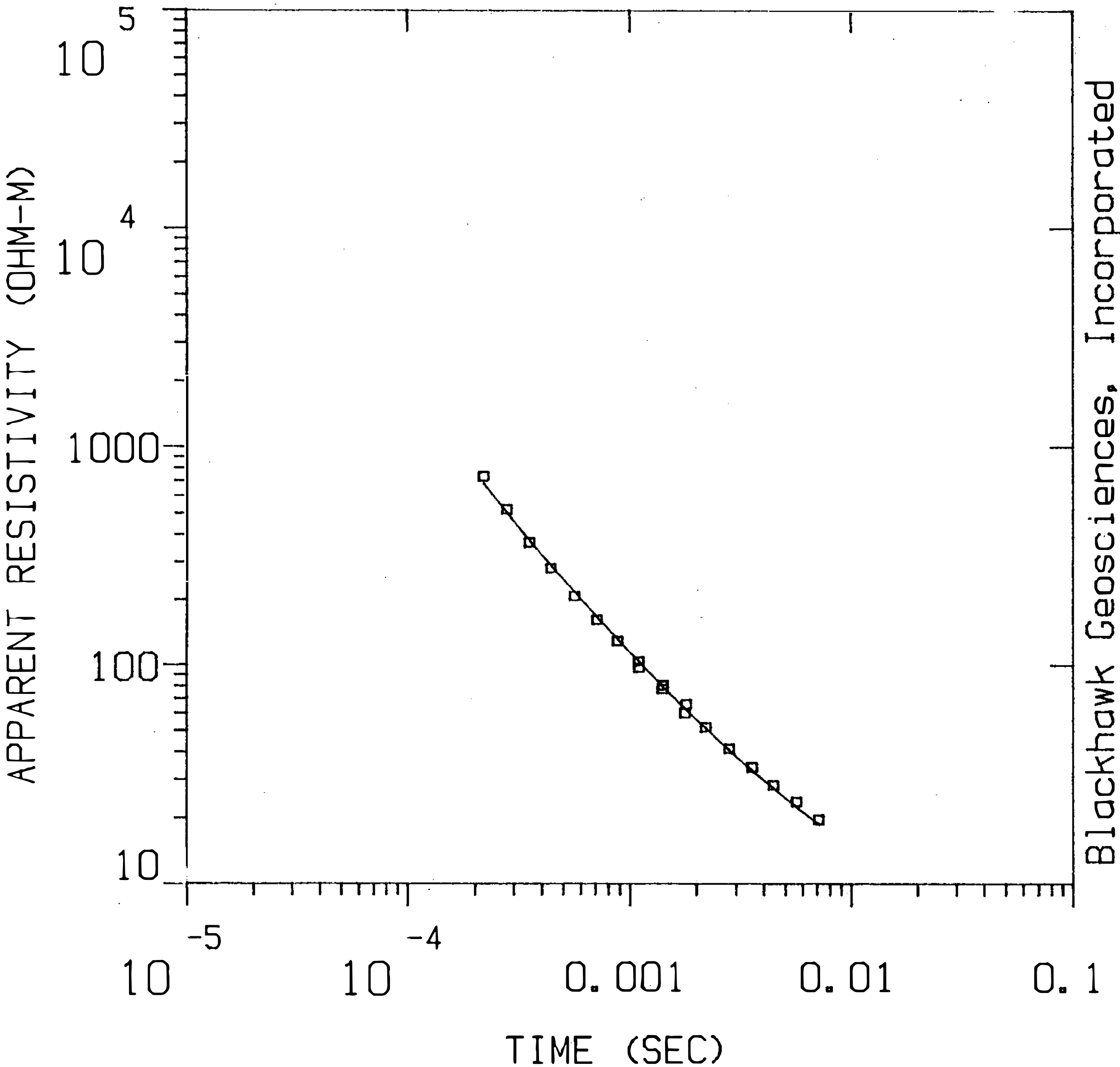
R: 152. X: 0. Y: 152. DL: 305. REQ: 169. CF: 1.0000
TDHZ ARRAY, 16 DATA POINTS, RAMP: 165.0 MICROSEC, DATA: WH1
2810 0000 0001 Z OPR XTL L 5 10+1000
Ch.21 = 0.165 Ch.22 = 0.89 Ch.23 = 15 Ch.24 = 9
RMS LOG ERROR: 1.39E-02, ANTILOG YIELDS 3.2483 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

	P 1	F 2	T 1
P 1	0.91		
F 2	0.00	0.00	
T 1	0.00	0.00	1.00

WH2



MODEL:

1429. OHM-M	209. M
2.80 OHM-M	

% ERROR: 6.20
CALIBRATION: 1
OFFSET: 76.2 M
RAMP: 110.0

MODEL: 2 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		167.6	550.0		
1429.36	209.0	-41.3	-135.6	0.1	0.1
2.80					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	2.20E-04	7.29E+02	6.81E+02	7.119	
2	2.80E-04	5.19E+02	5.03E+02	2.985	
3	3.55E-04	3.67E+02	3.77E+02	-2.526	
4	4.43E-04	2.79E+02	2.89E+02	-3.538	
5	5.64E-04	2.07E+02	2.18E+02	-4.882	
6	7.13E-04	1.61E+02	1.67E+02	-3.127	
7	8.81E-04	1.29E+02	1.32E+02	-2.120	
8	1.10E-03	1.04E+02	1.04E+02	0.017	
9	1.10E-03	9.70E+01	1.03E+02	-6.070	
10	1.40E-03	7.75E+01	8.03E+01	-3.498	
11	1.41E-03	8.06E+01	7.97E+01	1.138	
12	1.77E-03	5.99E+01	6.32E+01	-5.124	
13	1.80E-03	6.59E+01	6.23E+01	5.761	
14	2.20E-03	5.17E+01	5.11E+01	1.132	
15	2.80E-03	4.13E+01	4.08E+01	1.278	
16	3.55E-03	3.39E+01	3.29E+01	3.257	
17	4.43E-03	2.81E+01	2.73E+01	3.066	
18	5.64E-03	2.37E+01	2.24E+01	5.757	
19	7.13E-03	1.97E+01	1.87E+01	5.050	

R: 76. X: 0. Y: 76. DL: 152. REW: 84. CF: 1.0000
TDHZ ARRAY, 19 DATA POINTS, RAMP: 110.0 MICROSEC, DATA: WH2
1101 0002 2222 2 UPR XTL L 7 10+100
Ch.21 = 0.11 Ch.22 = 0.89 Ch.23 = 19 Ch.24 = 23
RMS LOG ERROR: 2.61E-02, ANTILOG YIELDS 6.1972 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

P 1	0.00		
F 2	0.00	0.00	
T 1	0.00	0.00	0.98
	P 1	F 2	T 1